UNCLASSIFIED

AD 265 342

Reproduced
by the

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

UNCLASSIFIED

Report No. 2

Second Quarterly Progress Report | Covering the Period 1 April to 30 June 1961

MICROWAVE FILTERS AND COUPLING STRUCTURES

Prepared for:

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

CONTRACT DA-36-039 SC-[illegible]
FILE NO. 40553-PM-61-93-93
DA PROJECT 3G26-12-031
SCL-2101K (20 APRIL [illegible])

By: W. J. Getsinger G. L. Matthaei

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

*SRI

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

July 1961

Report No. 2

Second Quarterly Progress Report | Covering the Period 1 April to 30 June 1961

MICROWAVE FILTERS AND COUPLING STRUCTURES

Prepared for:

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

CONTRACT DA-36-039 SC-87398
FILE NO. 40553-PM-61-93-93
DA PROJECT 3G26-12-001-02
SCL-2101K (20 APRIL 1959)

By: W. J. Getsinger G. L. Matthaei

SRI Project No. 3527

Objective: To advance the state of the art in the field of microwave filters and coupling structures through applied research and development.

Approved:

R. L. Tanner
R. L. TANNER, MANAGER ELECTROMAGNETICS LABORATORY

D. R. Scheuch
D. R. SCHEUCH, DIRECTOR ELECTRONICS AND RADIO SCIENCES LABORATORY

Copy No. 19

CONTENTS

ABSTRACT

Curves are presented giving the even mode fringing capacitance, the odd-mode fringing capacitance, and the difference between odd and even mode fringing capacitances for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to even and odd mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described.

An appendix gives the derivation of the fringing capacitances by conformal mapping techniques. The results are exact for bars extending in width infinitely far from the coupling region, and have only small error (less than 1.24 percent) for bars whose width is greater than about 35 percent of the difference between plate spacing and bar thickness.

Some previous work for the Signal Corps done at Stanford Research Institute presented design theory for lower or upper sideband up-converters for use as electronically tunable filters. Such devices were shown to have wide tuning range capability when designed using a wideband signal input impedance-matching filter, a moderately wideband pump input impedance matching filter, and a narrow-band output filter. Voltage control of the tuning can be achieved by using a voltage-tunable pump oscillator, since the pump frequency will control the frequency that will be accepted at the input of the amplifier. A trial strip-line lower-sideband up-converter was constructed using the previously developed theory. The measured 3-db bandwidth tuning range was 38.5 percent as compared to 40 percent for the design objective, and the peak gain was [illegible] db. The input band center was 946 Mc while the sideband output was at [illegible]. The noise figure has not yet been measured but an estimated value is [illegible] db.

ILLUSTRATIONS

I INTRODUCTION

Work on several preceding contracts, of which this present contract is an extension, included the development of design techniques for the precision design of various types of couplers and filters using parallel-coupled lines. Quarterly Progress Report 1 on this contract presented various design data for filters formed from arrays of parallel coupled conductors, such as occur in interdigital line. One very attractive way of constructing directional couplers or filters using such parallel-coupled line structures is to have the individual lines consist of rectangular bars centered between parallel ground planes. The data presented in Sec. II of this report make possible the precision design of such rectangular-bar, parallel-coupled lines. The data given will also be useful for determining the capacitance of many other structures having right-angle corners.

One of the problems being studied on this project is means for designing electronically tunable microwave filters. In the past a study was made of the feasibility of using variable-capacitance diodes as voltage controlled capacitors in filter circuits. In principle one can use capacitors to obtain voltage-tunable filters, but our studies showed that presently available capacitors have too low a Q to be of much use for voltage-tunable microwave filters, though they should be useful at lower frequencies.

Work is continuing on the use of ferrimagnetic resonance in yttrium-iron-garnet resonators which provide means for designing filters that can be tuned by varying a DC biasing magnetic field. This approach appears to hold considerable promise for electronic tuning applications at frequencies around 2 Gc or above.

Some previous work on this project dealt with design theory for variable-capacitance diode up-converters for use as electronically tunable filters. The amplifier is tuned by adjusting the pump frequency, where the pump oscillator would be of the voltage-tunable type. Using the previously developed design theory, a lower-sideband up-converter has been built and tested. The device and its measured performance are described in Sec. III.

II COUPLED RECTANGULAR BARS BETWEEN PARALLEL PLATES

A GENERAL

In working with shielded strip line, it is sometimes desirable to couple center conductors having appreciable thickness. The cross section of a typical structure of this type is shown in Fig. II-1. There are two parallel ground planes spaced a distance b apart, and two rectangular bars located parallel to and midway between the ground plane. It is well known[1,2]* that TEM propagation along such a structure can be described in terms of two orthogonal modes, usually denoted the even mode and the odd mode. In the even mode, both center conductors are at the same potential, while in the odd mode the two center conductors are at opposite potentials, with respect to the ground planes. These two TEM modes have different characteristic impedances, which are intimately related to the static capacitances of the bars to ground. These capacitances are given conventionally as parallel plate capacitances between bar and ground planes and fringing capacitances from ends and corners of the bars, as indicated schematically in Fig. II-1. This report presents graphs of the fringing capacitances for the two modes for wide ranges of bar thickness and spacing.

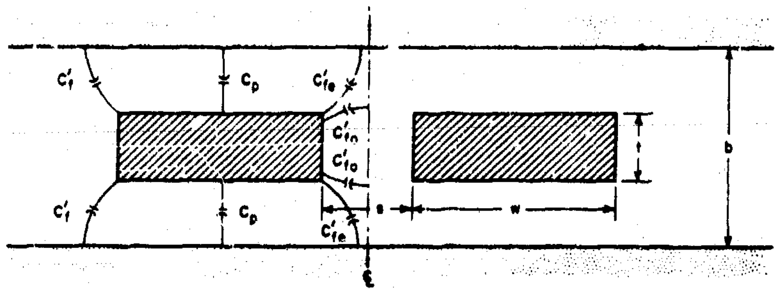

FIG. II-1 COUPLED RECTANGULAR BARS CENTERED BETWEEN PARALLEL PLATES

---
*References are listed at the end of the report.

The curves are based on an exact conformal mapping solution for bars extending in width infinitely far from the coupling region, and are applicable with negligible error for rectangular bars whose widths are greater than about 0.7 times that of the gap between the surface of a bar and the nearest ground plane.

B. TECHNICAL DESCRIPTION

The characteristic impedance, Z_o, of a lossless uniform transmission line operating in the TEM mode is related to its shunt capacitance by:

$$Z_o\sqrt{\epsilon_r} = \frac{\eta}{(C/\epsilon)} \text{ ohms} \qquad \text{(II-1)}$$

where

ϵ_r is the relative dielectric constant of the medium in which the wave travels

η is the impedance of free space = 376.7 ohms

C/ϵ is the ratio of the static capacitance per unit length between conductors to the permittivity (in the same units) of the dielectric medium (This ratio is independent of the dielectric constant.)

The even- and odd-mode impedances of coupled TEM lines[1,2] can be found by substituting even- and odd-mode capacitances of the lines into Eq. (II-1).

A generalized schematic diagram of shielded coupled strip transmission line is shown in Fig. II-2. The circles represent the coupled conductors. The capacitance to ground for a single conductor when both conductors are at the same potential is C_{oe}, the even-mode capacitance. The capacitance to ground when the two conductors are oppositely charged with respect to ground is C_{oo}, the odd-mode capacitance.

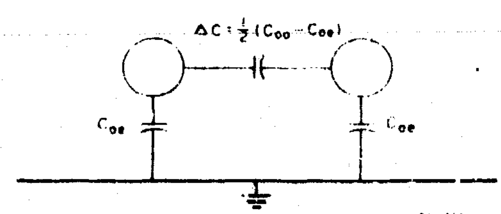

FIG. II-2 GENERALIZED SCHEMATIC DIAGRAM

The structure of Fig. II-1 is composed of parallel planar surfaces. This makes it practical to consider the total capacitance of a given strip to be composed of parallel-plane capacitances plus appropriate fringing capacitances. (Fringing capacitances take into account the distortion of the field lines in the vicinity of the edges of the plane strips.) Figure II-1 relates the various capacitances to the geometry of the structure under consideration. Thus, it can be seen that the total even-mode capacitance, C_{oe}/ϵ, from one bar to ground is

$$C_{oe}/\epsilon = 2(C_p/\epsilon + C'_{fe}/\epsilon + C'_f/\epsilon) \tag{II-2}$$

and the total odd-mode capacitance, C_{oo}/ϵ, from one bar to ground is

$$C_{oo}/\epsilon = 2(C_p/\epsilon + C'_{fo}/\epsilon + C'_f/\epsilon). \tag{II-3}$$

In Eqs. (II-2) and (II-3), C_p is the parallel-plate capacitance of the top or bottom side of one bar to the nearest ground plane, C'_{fe} is the capacitance to ground from one corner and half the associated vertical wall in the coupling region of a bar for even mode excitation, C'_{fo} is the capacitance to ground from one corner and half the associated vertical wall in the coupling region of a bar for odd-mode excitation, and C'_f is the capacitance to ground from one corner and half the associated vertical wall away from the coupling region of a bar for any excitation. Consideration of Fig. II-2 and the definitions of even and odd mode capacitances show that the capacitance, $\Delta C/\epsilon$, from one bar to the other is given by

$$\Delta C/\epsilon = \frac{1}{2}(C_{oo}/\epsilon - C_{oe}/\epsilon) \quad . \tag{II-4}$$

Subtraction of Eq. (II-2) from (II-3) shows that $\Delta C/\epsilon$ can be written entirely in terms of the fringing capacitances as

$$\Delta C/\epsilon = C'_{fo}/\epsilon - C'_{fe}/\epsilon \tag{II-5}$$

Figure II-3 is a plot of both even-mode fringing capacitance, C'_{fe}/ϵ, and the capacitance, $\Delta C/\epsilon$, between bars as functions of bar thickness and spacing while Fig. II-4 is a similar graph for the odd-mode fringing capacitance, C'_{fo}/ϵ. The derivation of Figs. II-3 and II-4 is described in the Appendix. Figure II-5 gives the fringing capacitance, C'_f/ϵ, from the outer edges of the bars as a function of thickness. The parallel plate capacitance, C_p/ϵ, is given by

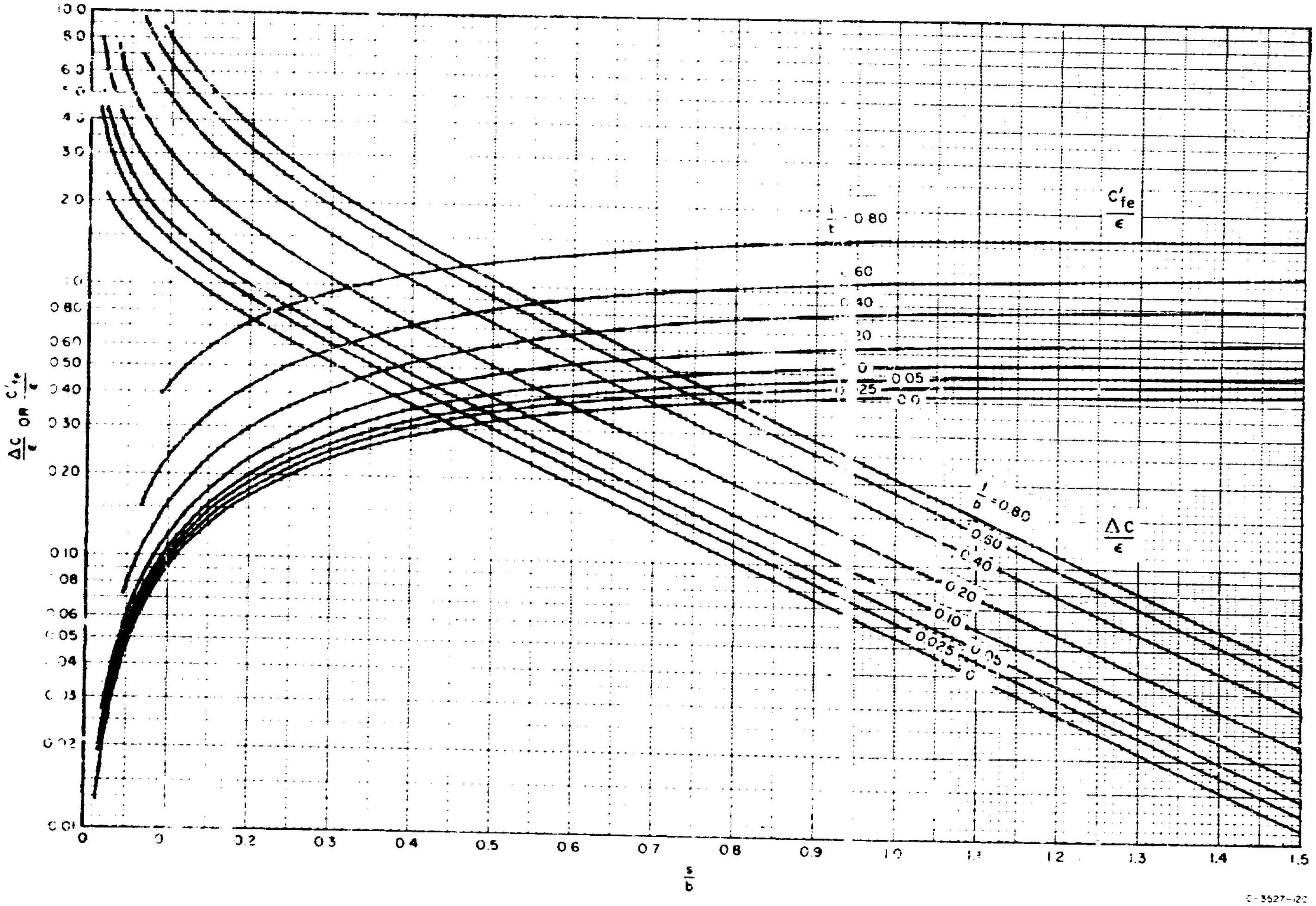

FIG II-3 FRINGING CAPACITANCES FOR COUPLED RECT NGULAR BARS

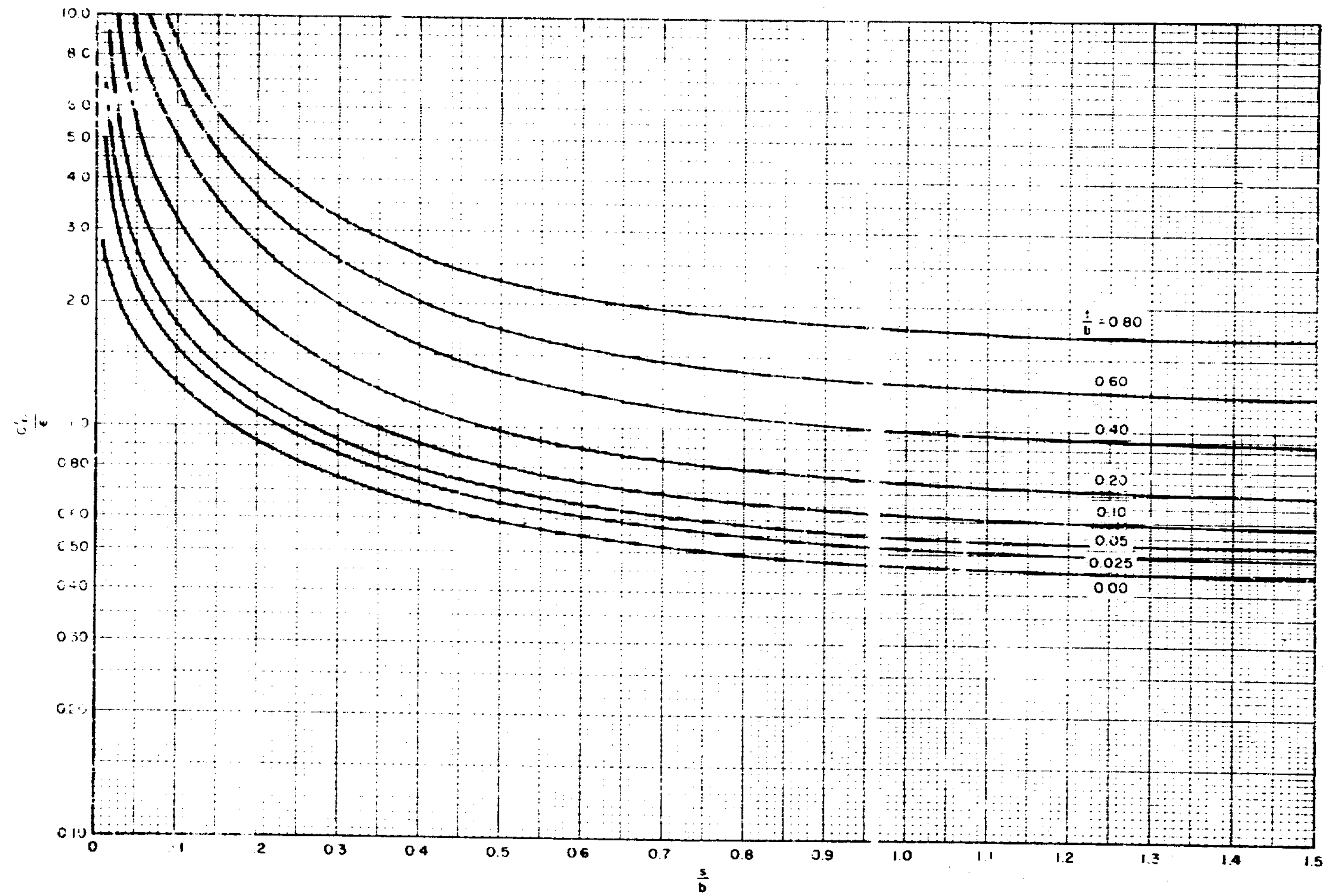

FIG. II-4 ODD-MODE FRINGING CAPACITANCE FOR COUPLED RECTANGULAR BARS

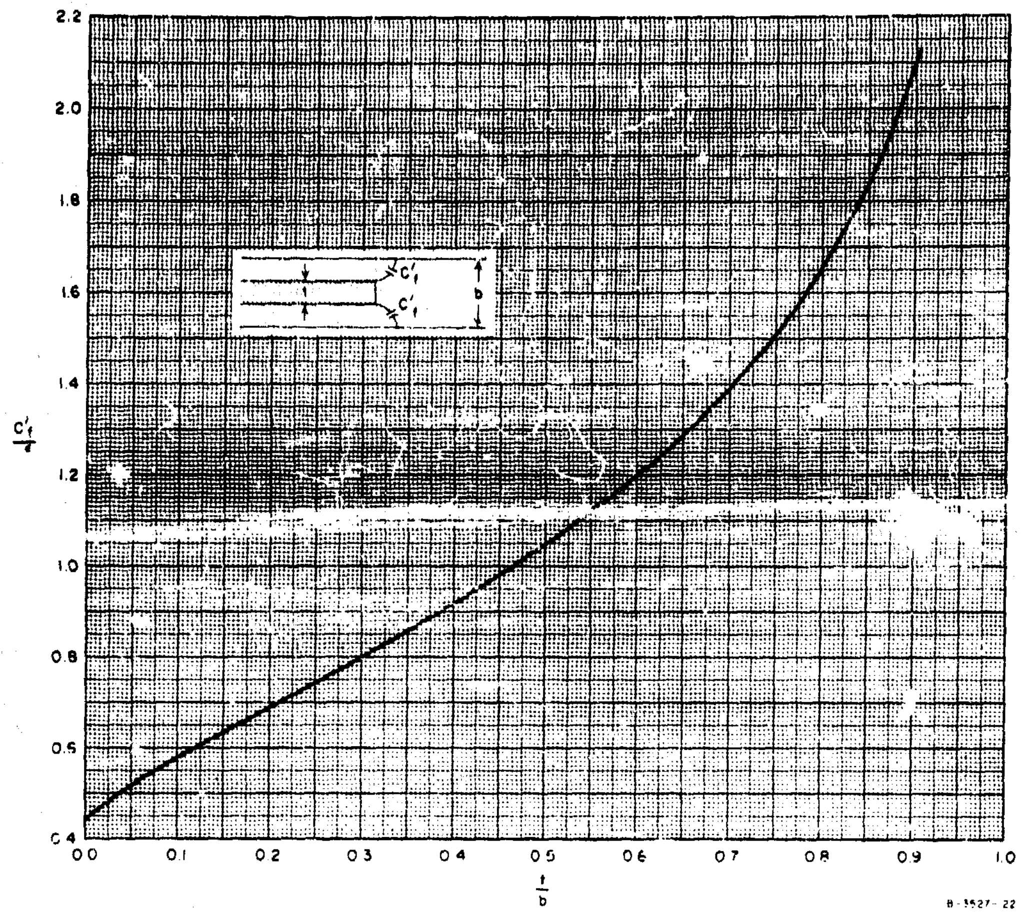

FIG. II-5 FRINGING CAPACITANCE FOR AN ISOLATED RECTANGULAR BAR

$$C_p/\epsilon = 2\,\frac{w/b}{1 - t/b} \qquad \text{(II-6)}$$

where w and t are the width and thickness of the bar. Through the use of the above relations and figures, it is possible to relate physical dimensions of the given configuration to even- and odd-mode capacitances or impedances.

C USE OF THE GRAPHS

Usually an engineer designing parallel-coupled lines first determines the values of even- and odd-mode impedances, Z_{oe} and Z_{oo}, [illegible] odd-mode capacitances, C_{oe} and C_{oo}, as required by theoretical considerations. He then wishes to determine the corresponding physical line dimensions. A simple procedure accomplishes this. Using Eq. (II-1) in Eq. (II-4) gives

$$\Delta C/\epsilon = \frac{\eta}{2\sqrt{\epsilon_r}}\left(\frac{1}{Z_{oo}} - \frac{1}{Z_{oe}}\right) \quad . \qquad \text{(II-7)}$$

Values of b and t are selected, and used with the value of $\Delta C/\epsilon$ found from Eq. (II-7) to determine s/b directly from Fig. II-3. Next, C_{oe}/ϵ is determined by using Z_{oe} in Eq. (II-1), and then C'_{fe}/ϵ and C'_f/ϵ are found from t/b and from the graphs of Figs. II-3 and II-5. These quantities can be substituted into the following equation to give w/b:

$$w/b = \frac{1}{2}\left(1 - \frac{t}{b}\right)\left(\frac{C_{oe}/\epsilon}{2} - C'_{fe}/\epsilon - C'_f/\epsilon\right) \quad . \qquad \text{(II-8)}$$

Equation (II-8) results from substitution of Eq. (II-6) into Eq. (II-2) and rearrangement of terms.

Thus, the two unknown dimensions, s/b and w/b, have been determined.

D. CONSIDERATIONS OF ACCURACY

If the bar width, w, is allowed to become too small, then there is interaction of the fringing fields from the two edges, and the decomposition of total capacitance into parallel plane capacitance and fringing capacitances (which are based on infinite bar widths), is no longer accurate. Cohn[3] shows that for a single bar centered between parallel planes, the error in total capacitance from interaction of the fringing fields is about 1.24 percent for $w/(b - t) = 0.35$, where w is the width of the bar, t is its thickness, and b is again the ground-plane spacing. If a maximum error in total capacitance of approximately this magnitude is allowed, then it is necessary that $[(w/b)/(1 - t/b)] > 0.35$.

Should this inequality be too restricting, it is possible to make approximate corrections based on increasing the parallel-plate capacitance to compensate for the loss of fringing capacitance due to interaction of fringing fields. If an initial value, w_1/b is found to be less than $0.35[1 - (t/b)]$, a new value, w_2/b can be used, where

$$w_2/b = \{0.07[1 - (t/b)] + w_1/b\}/1.20 \qquad \text{(II-9)}$$

provided $0.1 < (w_2/b)/[1 - (t/b)] < 0.35$. This formula is based on a linear approximation to the exact fringing capacitance of single thin strip for a $(w/b)/[1 - (t/b)]$ ratio between 0.1 and 0.35. As the relative strip width becomes narrower than 0.35, the fringing capacitance, defined as total capacitance less parallel plate capacitance, becomes smaller. The total capacitance is given by substituting into Eq. (II-1) the exact thin-strip formula for Z_0 given in Ref. 6. Equation (II-9) adds sufficient parallel-plate capacitance to compensate for the loss of fringing capacitance. The loss of fringing is assumed to vary linearly below a relative width of 0.35. Although the formula is analytically only approximate, it is sufficiently accurate for practical use because it does no more than give a small correction to a quantity that is reasonably close to the exact value. It can be [illegible] both isolated and coupled bars.

The derivations for the fringing capacitances are exact for bars extending in width infinitely far to the right and left away from the coupling region. The original computed values were accurate to eight places. However, in order to give values of fringing capacitance associated with constant t/b, it was necessary to use graphical interpolation, as pointed out in the appendix. The plotted points were held to an accuracy of three figures after the decimal point, so that the interpolated results are slightly less accurate. The curves of Fig. II-3 and II-4 are accurate to within about one or two percent. However, since fringing capacitances are usually not the predominant part of the total capacitance of a structure, total capacitance can be specified with somewhat greater accuracy.

Figure II-5, for the fringing capacitance, C'_f/ϵ, of a single bar extending infinitely far in one direction, is based on an exact solution given by Cohn.[3] The same data can be found from Figs. II-3 and II-4 by reading either C'_{fe}/ϵ or C'_{fo}/ϵ as functions of t/b for large s/b. The accuracy of Fig. II-5 is thus limited by the precision to which the graph can be read.

E. APPLICATIONS

Figures II-3, II-4, and II-5 for fringing capacitances can be used for a variety of structures, as shown in Fig. II-6, simply by adding the appropriate fringing capacitances with the parallel plate capacitances to give the even-mode capacitance, the odd-mode capacitance, or the total capacitance. Use of Eq. (II-1) then gives the associated characteristic impedance.

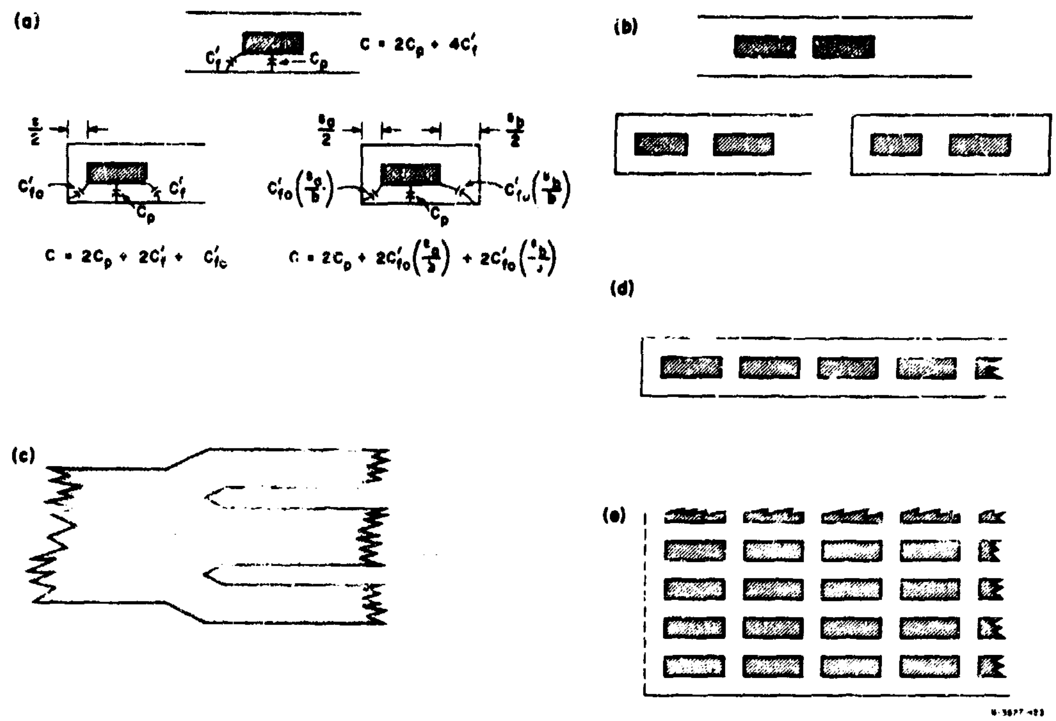

FIG. II-6 POSSIBLE APPLICATIONS

Thus, (a) in Fig. II-6 shows ordinary shielded strip-line and the capacitances involved when it is open, closed at one end, or closed at both ends.* The structure closed at one end is sometimes called trough-line, the structure closed at both ends is sometimes called rectangular coaxial line. Similarly, the even- and odd-mode capacitances and impedances can be determined for the coupled structures shown in (b) of Fig. II-6 for open or closed ends. This simple technique may also be applicable when the arms of an N-way power divider in shielded strip-line must run parallel for some distance, as shown in plan in (c) of Fig. II-6. The even-mode fringing capacitance, C'_{fe}, would then be appropriate for adjacent edges of the arms.

* The notation in Fig. II-6(a), $C'_{fo}(S_a/b)$ and $C'_{fo}(S_b/b)$, does not indicate multiplication, but merely that C'_{fo} is to be evaluated at S_a/b or S_b/b, as appropriate for the spacing from the nearby wall.

Both even- and odd-mode fringing capacitances would be necessary for multi-element lines, such as are shown in (d) and (e) of Fig. II-6. The cross section shown in (d) could be part of a meander or interdigital line, while that in (e) might be part of a finite or infinite array of elements, which might be used as an artificial dielectric medium.

The curves given herein can be used in the design of wide-band, parallel-coupled, strip-transmission-line filters, such as described by Matthaei.[4] Also, Bolljahn and Matthaei[5] have presented design data for slow-wave structures and filters using parallel coupled arrays of line elements. Some realization of those devices use relatively wide rectangular bars to form an interdigital line, comb line, meander line, or similar slow-wave line. In such cases, the curves given herein greatly facilitate the process of precision design.

Another application of coupled rectangular bars is to strip-line directional couplers, described by Jones and Bolljahn[2], in which the use of rectangular bars allows closer coupling to be achieved with less critical tolerances.

III AN EXPERIMENTAL ELECTRONICALLY TUNABLE UP-CONVERTER

A. DESCRIPTION OF THE DEVICE

The up-converter discussed herein achieves electronic tuning over a wide bandwidth by use of a wideband signal input circuit, a wideband pump input circuit, and a narrow-band lower sideband output circuit. For a signal to be passed by the amplifier, the frequency relation

$$f = f^p - f_0' \quad \text{(III-1)}$$

must be satisfied, where f is the signal input frequency, f^p is the pump frequency, and f_0' is the output frequency. Since the frequency f_0' is fixed by the narrow-band output circuit, the input acceptance frequency can be controlled by varying the pump frequency. With the use of a voltage-tunable pump oscillator such as a carcinotron, the amplifier can be made to be voltage tunable.

Figure III-1 shows a semi-lumped equivalent circuit for the amplifier. The varactor diode is resonated in series by cascading it with a transmission line having a high characteristic impedance (Z_0 = 207 ohms). In the circuit

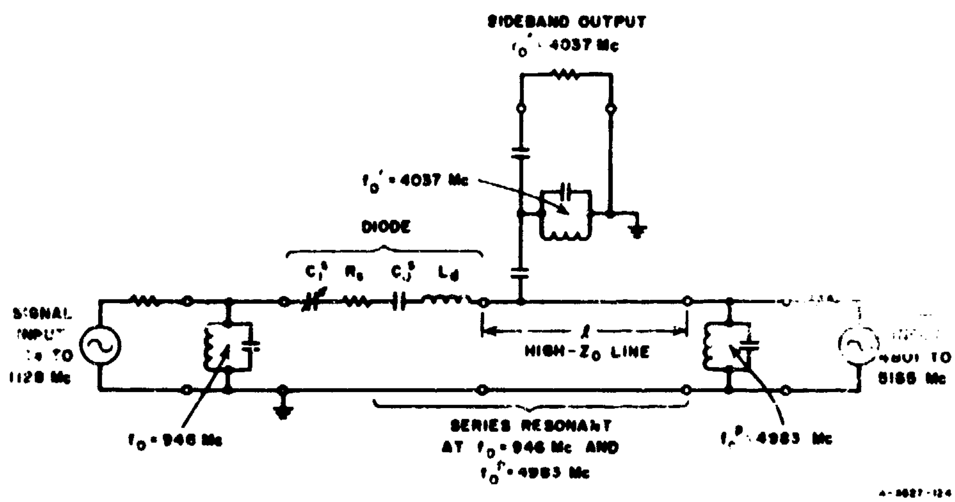

FIG. III-1 EQUIVALENT CIRCUIT OF THE UP-CONVERTER DISCUSSED HEREIN as shown, the diode and high-Z_0 line exhibit series resonance at f_0, the center of the input frequency band, and also at f_0^p, the center of the pump-frequency band. On the left is a shunt resonator which is also resonant at f_0. The shunt resonator on the left plus the f_0 series-resonance of the diode circuit provide a two-resonator-input impedance-matching filter. The shunt resonator on the right (which is resonant at f_0^p) along with the f_0^p series-resonance of the diode circuit provide a two-resonator impedance-matching filter for broadbanding the pump circuit. At the top of Fig. III-1 is shown an output resonator that has loose, capacitive coupling. This resonator has a sharp resonance at the lower-sideband frequency, f_0', and provides the required lower-sideband termination and output circuit. Design theory for electronically tunable up-converters of this sort has been presented previously.[6,7]

Figure III-2 shows a simplified drawing of the strip transmission-line realization of the circuit in Fig. III-1. The diode used is a Hughes 1N896 diode in a computer type of package. The 0.020-inch-diameter wire leads of the diode provide the high-Z_0 line to resonate the diode. The input, shunt-tuned circuit is realized as a short inductive stub in parallel with a capacitor block having thin dielectric at its top and bottom. The shunt-tuned resonator at the pump input in Fig. III-1 was replaced by a modified form of resonator[8] consisting of a nominally quarter-wavelength line with inductive coupling to the diode circuit and capacitive coupling to the pump input line. The lower-sideband resonator is of the half-wavelength type, with capacitive coupling to the diode circuit and to the output line. Capacitively coupled, half-wavelength, band-stop resonators were added at the pump and signal input lines to prevent any leakage of the lower-sideband signal. The signal input line (on the right) had a step transformer to raise the input impedance from 50 to 62 ohms.

Figure III-3 shows a photograph of the strip-line amplifier with its cover plate removed. It had been planned originally to use a quarter-wavelength resonator for the lower-sideband output utilizing inductive coupling to the diode circuit and capacitive coupling to the output line. This, however, did not prove entirely satisfactory, since it was difficult to make the inductive coupling as tight as desired. As a result, the somewhat makeshift half-wavelength output resonator shown in Fig. III-3 was inserted, using capacitive coupling at both ends. It was necessary to make this output resonator S-shaped in order to make it fit into the space available. Provision was made for applying external bias to the

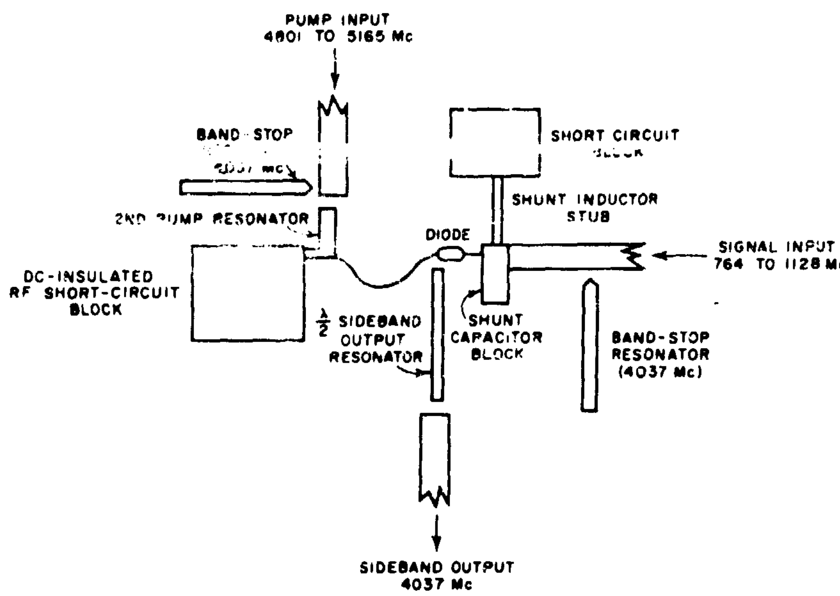

FIG. III-2 SIMPLIFIED DRAWING OF THE STRIP-TRANSMISSION LINE ELECTRONICALLY TUNABLE UP-CONVERTER

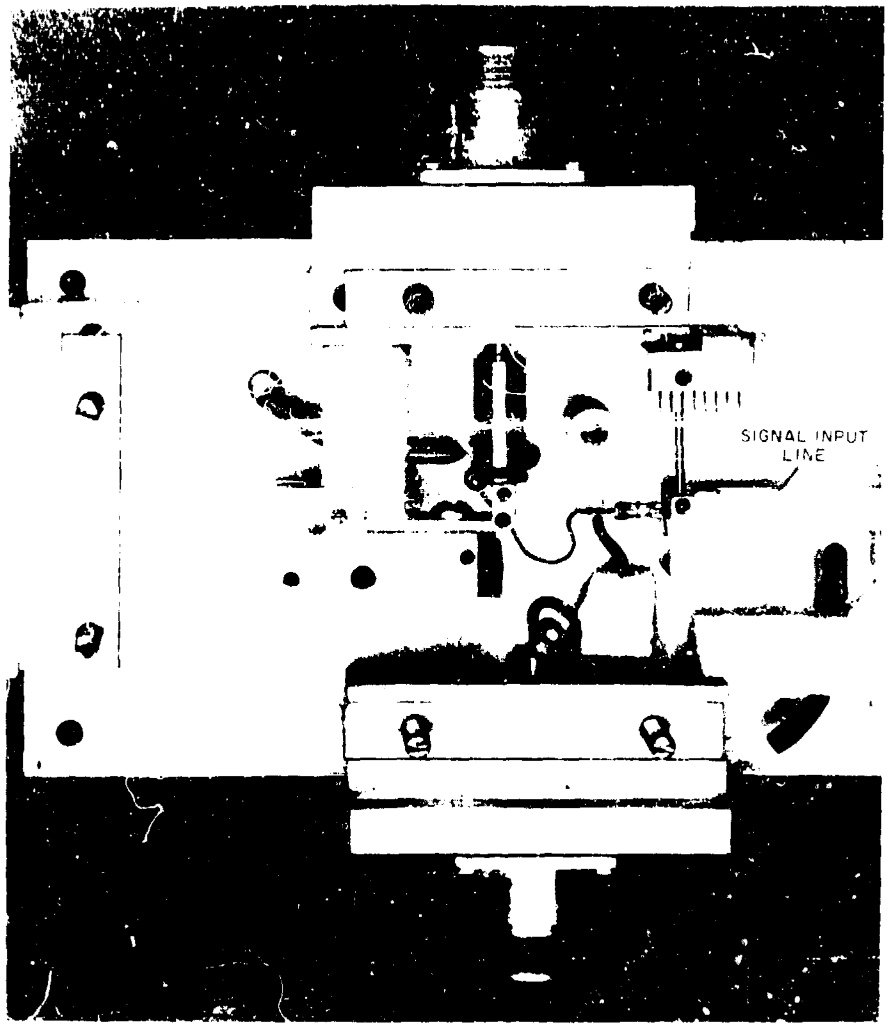

FIG. III-3 PHOTOGRAPH OF THE ELECTRONICALLY TUNABLE UP-CONVERTER WITH ITS COVER PLATE REMOVED diode by use of a fine wire lead seen at the left in Fig. III-3, but the device was operated with the diode DC-bias connection open-circuited. This method of operation provides self-bias when the diode is pumped.

B. MEASURED PERFORMANCE

For a device of this type to be practical it is necessary that an impedance-matching filter be used to broaden the bandwidth of the pump input circuit.[6,7] Since most of the pump energy is absorbed in the diode resistance, which is quite small, and since the reactance slope of the diode-circuit resonance at the pump frequency is quite large, a broadband, low-VSWR match is not possible. However, the reflection loss can be kept to a minimum and made to be quite uniform across the required pump bandwidth by use of a properly designed impedance-matching filter. Figure III-4 shows the reflection loss in the pump channel of the amplifier, as computed from measured VSWR. The reflection loss is seen to be constant within ±0.2 db from 4.81 to 5.26 Gc.

Figure III-5 shows the measured tuning characteristics of the amplifier. The points on this response were obtained by setting the pump frequency, and then adjusting the single input frequency until an output frequency of exactly 4,037 Mc was obtained. The output frequency was held directly to 4,037 Mc since, in typical cases, an amplifier of this sort might be followed by a superheterodyne receiver of quite narrow bandwidth. All of the points were taken with an incident pump power level of 67 mw in order to simulate operation with a pump source having constant incident output power. This level of pumping is less than that giving maximum gain but it should be about right for optimum noise figure.

The tuning bandwidth of the amplifier is seen to be 38.5 percent, which is in satisfactory agreement with the design value of 40 percent. The peak gain of 12.6 db was chosen as a practical compromise value. (Higher gain can be achieved by adjusting the coupling of the lower-sideband output resonator.) Since about 6 db of the gain is due to the frequency ratio f_0''/f_0, the negative-resistance component of gain is [illegible] that of most parametric amplifiers, which makes the amplifier relatively insensitive to termination VSWR. However, even with a gain of around 10 db, the amplifier can still serve as a low-noise preamplifier as well as an electronic tuner.

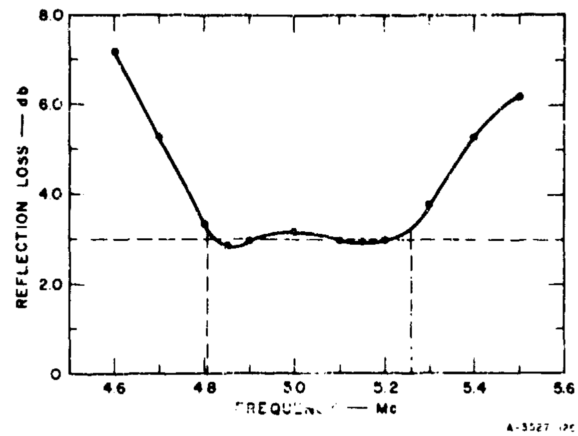

FIG. III-4 REFLECTION LOSS AT PUMP INPUT PORT AS COMPUTED FROM MEASURED VSWR

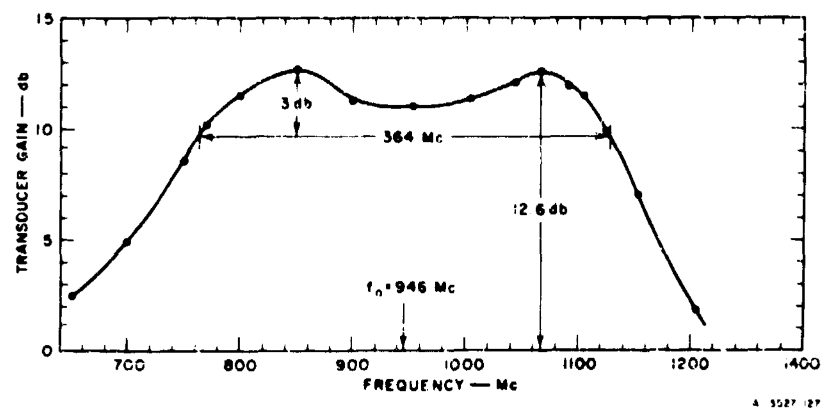

FIG. III-5 MEASURED TUNING CHARACTERISTICS OF UP-CONVERTER
(The output frequency was held fixed at 4037 Mc while the pump frequency was varied for each input frequency; incident pump power was a constant 67 mw.)

C. NOISE FIGURE

At midband the resonators of the input and output filters are at resonance so that the filter circuits present purely real impedances to the time-varying component of the diode capacitance.[6,7] For purposes of analysis the circuit can then be reduced to the simplified circuit in Fig. III-6. In that figure R_{b0} is the resistance presented by the input filter, R'_{b0} is the resistance coupled in by the lower-sideband output resonator, R_s is the diode resistance plus any other series resistance seen at the midband input frequency f_0, while R'_s is the diode resistance plus any other series resistance seen at the lower sideband frequency f'_0. The box marked $(X_{12}X_{21})_0$ represents the coupling effect of the time-varying component of the diode capacitance, and[6,7]

$$(X_{12}X_{21})_0 = \frac{(C_1/C_0)^2}{(2\pi f_0 C_0)(2\pi f'_0 C_0)\left[1 - \left(\frac{C_1}{C_0}\right)^2\right]^2} , \qquad \text{(III-2)}$$

The Fourier-series capacitance coefficients C_0 and C_1 are defined as indicated by the expression

$$C(t) = C_0 + 2C_1 \cos\,(2\pi f_p t + \phi_p) + \cdots , \qquad \text{(III-3)}$$

for the capacitance of a pumped diode. In Fig. III-6, R_s and R'_s are both assumed to be at temperature T_d but R_{b0} and R'_{b0} may be at other temperatures T_i and T'_i, respectively.

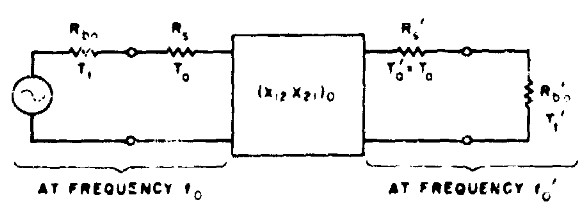

FIG. III-6 DEFINITION OF PARAMETERS FOR DETERMINING THE AMPLIFIER MID-BAND NOISE FIGURE

Using the above definitions it can be shown that the midband noise figure of a lower-sideband up-converter is*

$$F = \left(1 + \frac{R_s}{\alpha R_{b0}}\right) + \frac{f_0}{f_0'}\,\frac{\alpha'}{\alpha}\,\frac{R_{b0}R_{b0}'}{(X_{12}X_{21})_0}\left\{\left(1 + \frac{R_s'}{\alpha' R_{b0}'}\right)\left(1 + \frac{R_s}{R_{b0}}\right)^2 - \frac{1}{4}\left[\left(1 + \frac{R_s}{R_{b0}}\right)\left(1 + \frac{R_s'}{R_{b0}'}\right) - \frac{(X_{12}X_{21})_0}{R_{b0}R_{b0}'}\right]^2\right\} \qquad \text{(III-4)}$$

where

$$\alpha = \frac{T_t}{T_a} \quad \text{and} \quad \alpha' = \frac{T_t'}{T_a} \qquad \text{(III-5)}$$

For the amplifier described, approximate values for the various parameters are $R_{b0} = 62.3$, $R_{b0}' = 11.5$, $f_0'/f_0 = 4.27$, $(X_{12}X_{21})_0 = 410$, $R_s = 4$, and $R_s' = 4.75$. The R_s and R_s' values given include diode resistance plus estimated resistance due to input and output circuit loss. Assuming that the amplifier and the terminations are all at the same temperature so that $\alpha = \alpha' = 1$, the estimated midband noise figure is then 2.1 db. The noise figure will change some at tuning frequencies other than midband, but it should not vary much within the operating band.

Figure III-7 shows a possible way of operating the amplifier when extremely high sensitivity is desired. In this circuit a circulator is used at the lower-sideband output so that a "cold" termination can be introduced. Recent data[9] indicate that at 4 Gc the sky has a temperature of about 3°K. Thus, the cold termination could be obtained by pointing a directional antenna at the sky. In this manner the circuit shown in Figure III-7 would provide a cold termination for the lower sideband, while at the same time providing a readily accessible output port. [illegible]ator would also cause any excess noise from the superheterodyne re[illegible] radiated to the sky, which would prevent such excess noise from degrading the up-converter noise figure. An isolator is shown at the input of the up-converter which would make the system absolutely stable, regardless of the input termination.

---

* This expression assumes that the only noise present is the thermal noise in R_s, R_{b0} and R_{b0}'. Such an assumption is usually satisfactory.

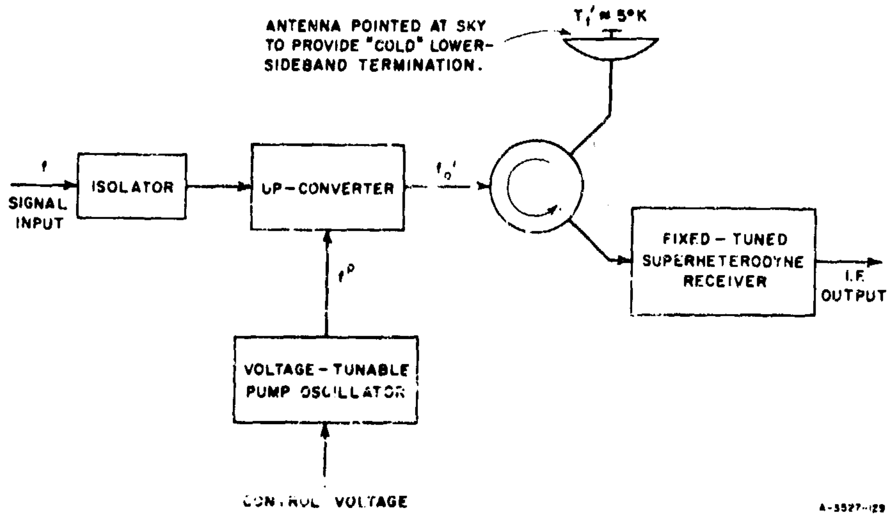

FIG. III-7 POSSIBLE SYSTEM FOR USING ELECTRONICALLY TUNABLE UP-CONVERTER WHERE EXTREMELY HIGH SENSITIVITY IS DESIRED (The circulator and the antenna pointed at the sky are introduced to give an extremely low noise figure. They are not essential to the operation of the system.)

Taking $T_a = T_t = 290°K$, while assuming $T_t' = 5°K$, then $\alpha = 1$ and $\alpha' = 0.01725$. The estimated noise figure for the up-converter in Fig III-7 is then 0.98 db. If the isolator at the input had 1.0 db insertion loss, this noise figure would be raised to 1.98 db. Assuming that the fixed tuned superheterodyne receiver has a noise figure of 7 db, the midband system noise figure would then be 2.78 db (assuming 11 db midband amplifier gain as indicated in Fig. III 5).

Laboratory procedures to measure the noise figure of the amplifier have been started, but they have not been completed at the time of this writing.

IV CONCLUSIONS

A. COUPLED RECTANGULAR BARS BETWEEN PARALLEL PLATES

The charts of fringing capacitances presented should be useful for a large variety of microwave engineering problems. Some applications of immediate interest are the precision design of directional couplers using parallel-coupled rectangular bars between ground planes and interdigital line filters consisting of parallel arrays of bars having rectangular cross sections.

B. ELECTRONICALLY TUNABLE UP-CONVERTER

The experimental electronically tunable up-converter performed very much as predicted by the previously developed theory.[6,7] Approximate calculations previously presented[6,7] indicate that it should be practical to design such devices for tuning ranges as large as an octave. The previous estimates along with the results presented herein show that electronically tunable up-converters provide a practical way to obtain electronic tuning for large bandwidths in frequency ranges extending from a few megacycles up to the range where the garnet filters being studied on this contract can be used for electronic tuning (2 Gc and higher). By using the new high-Q diodes, and possibly by using diodes in a push-pull configuration, electronically tunable up-converters having input frequencies significantly above 2 Gc may be possible. The estimated noise figure of the trial amplifier indicates that it has potential value as a low-noise preamplifier as well as an electronic tuner.

PROGRAM FOR THE NEXT INTERVAL

It is anticipated that the work for the next interval will include:

(1) Further work on filters with magnetically tunable garnet resonators

(2) Further work on interdigital line filters

(3) Work on band-stop filters

(4) Work on microwave filter book.

IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Dr. P. S. Carter, Jr. *Senior Research Engineer*	PART TIME
Mr. W. J. Getsinger *Senior Research Engineer*	PART TIME
Dr. E. M. T. Jones *Head, Microwave Group*	PART TIME
Dr. G. L. Matthaei *[illegible]*	PART TIME
Dr. Leo Young *Senior Research Engineer*	PART TIME

APPENDIX

DERIVATION OF FRINGING CAPACITANCES

APPENDIX

DERIVATION OF FRINGING CAPACITANCES

1. PRELIMINARY

It is desired to determine the static fringing capacitances shown on the structure of Fig. II-1 by means of conformal mapping techniques.[10,11] This can be done by subjecting the boundaries of the structure to transformations under which capacitance is invariant, and that lead to a new structure for which capacitance is known. Subtraction of parallel plate capacitances of the original structure from the total capacitance then leaves the fringing capacitances. The analysis will be limited to structures in which the bars are so wide that interaction between fringing fields of the two edges of a single bar are negligible. As discussed in Sec. II-D, this requires that the approximate relation $\{(w/b)/[1 - (t/b)]\} > 0.35$ be held. Under these conditions it is possible to let the bars extend in width infinitely far to the left and right without disturbing the fringing fields appreciably in the coupling region where the capacitances interact. The vertical centerline shown on Fig. II-1 may be replaced by an electric wall (conductor) for the odd mode, or by a magnetic wall for the even mode, in consideration of the symmetry of the structure. Also, the electric field can lie parallel to the horizontal centerline where no conductor exists, but cannot cross it because of the symmetry. Therefore, a magnetic wall can be placed along the horizontal centerline. These modifications allow analysis of only one-quarter of the total symmetrical structure. The mathematical model is shown on the z-plane in Fig. A-1. Conductors are indicated by solid lines and magnetic walls by dashed lines. The upper-case letters denote pertinent points of the structure and will serve as references when transformations to different complex planes are made.

The analysis consists essentially in transforming the contours of the structure on the z-plane into a parallel-plate representation on another complex plane, where capacitance can be computed directly.

The static electric fields of interest lie within the polygon defined by the boundaries of the structure on the z-plane. The interior of this

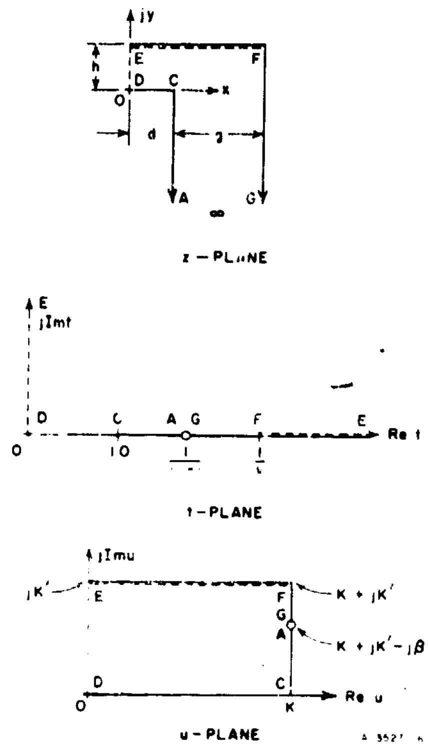

FIG. A-1 MATHEMATICAL MODELS ON z-PLANE, t-PLANE, AND u-PLANE

polygon is to be mapped onto the first quadrant of the t-plane shown in Fig. A-1. The integral resulting from direct use of the Schwarz-Christoffel transformation is

$$z = \int \frac{(1 - t^2)^{1/2}}{(1 - k^2 t^2)^{1/2}(1 - k^2 t^2 \operatorname{sn}^2 a)} \, dt \quad , \tag{A-1}$$

where, for the present, $1/k$ and $1/(k \operatorname{sn} a)$ are the points on the real axis to which the corner F and the point $-j\infty$ map from the z-plane. This integral can be evaluated by further relating the first quadrant of the t-plane to the interior of the fundamental rectangle of Jacobian elliptic functions on the u-plane, also shown on Fig. A-1, using the transformation

$$t = \operatorname{sn} u \quad . \tag{A-2}$$

This substitution gives

$$z = \int \frac{\mathrm{cn}^2\, u\, du}{1 - k^2\, \mathrm{sn}^2\, u\, \mathrm{sn}^2\, a} \tag{A-3}$$

In the above equations, sn u and cn u are Jacobian elliptic functions having a quarter-period $4K$ determined by k, denoted by convention as the modulus. By virtue of Eq. (A-2), a can be considered to be a point on the perimeter of the fundamental rectangle on the u-plane. It is convenient to let

$$a \triangleq K - j\beta \tag{A-4}$$

by definition. [illegible] be used as independent variab[illegible]

The mapping of the z-plane onto the t-plane in this manner has been carried through by Cockroft[12] whose symbols are retained in Fig. A-1 and in the equations given in this section. The distances on the z-plane are given by Cockroft as

$$d = K \left[1 - \frac{\mathrm{dn}\, a}{k^2\, \mathrm{sn}\, a\, \mathrm{cn}\, a} Z(a)\right] \tag{A-5}$$

$$g = -j \frac{\pi}{2} \frac{\mathrm{dn}\, a}{k^2\, \mathrm{sn}\, a\, \mathrm{cn}\, a} \tag{A-6}$$

$$h = jd \frac{K'}{K} - j \frac{\pi}{2} \frac{\mathrm{dn}\, a}{k^2\, \mathrm{sn}\, a\, \mathrm{cn}\, a} \left(\frac{a}{K} - 1\right) \tag{A-7}$$

It should be noted that g is a negative quantity and h an imaginary one. The quantity dn a is also a Jacobian elliptic function and $Z(a)$ is the Jacobian Zeta-function. The quantity K' is the same function of the complementary modulus k', as K is of k. The moduli are related by

$$k^2 + k'^2 = 1. \tag{A-8}$$

Comparison of Fig. II-1 with Fig. A-1 shows that the conventional normalized dimensions, s/b and t/b, of the rectangular bar structure are related to Cockroft's dimensions, d, g, and h, by

$$
\begin{aligned}
s/b &= \frac{-jh}{d-g} \\
t/b &= \frac{d}{d-g} \quad .
\end{aligned}
\tag{A-9}
$$

Thus, the physical dimensions of the structure of Fig. II-1 have been related to the parameters of the u-plane by Eqs. (A-5), (A-6), (A-7), and (A-9).

Now it is necessary to transform the t-plane to a parallel-plate structure, and determine fringing capacitances as functions of u-plane parameters

2. ODD MODE CAPACITANCE

The two rectangular bars in Fig. II-1 are at equal and opposite voltages when energized in the odd mode, so that the plane midway between the bars is at zero potential. Thus, a conductor may be placed in this plane without disturbing the fields. This is indicated by the solid line between E and F on the planes of Fig. A-1. For this condition, the t-plane configuration can be transformed to a parallel-plate structure of unit height by the function

$$
w = \frac{1}{\pi} \, ln \left(\frac{1 + t \, k \, \mathrm{sn} \, a}{1 - t \, k \, \mathrm{sn} \, a} \right) \quad , \tag{A-10}
$$

which moves the singularity at AG to infinity. The interesting region of the w-plane is shown in Fig. A-2

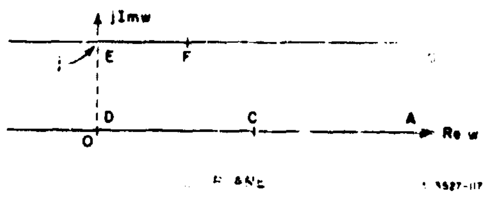

FIG. A-2 w-PLANE FOR ODD-MODE CAPACITANCE

The fringing capacitance is the difference between the total capacitance of the structure (total capacitance is the same on both z- and w-planes) and the parallel-plane capacitance of the z-plane structure. A reasonable definition for z-plane parallel-plate capacitance, C_{pz}, is parallel-plate capacitance existing between the ground plane and the full length of the rectangular bar. Mathematically,

$$\frac{C_{pz}}{\epsilon} = \lim_{z \to -j\infty} Im(z/g) \quad . \tag{A-11}$$

Then the odd-mode fringing capacitance, C'_{f0}/ϵ, is

$$C'_{f0}/\epsilon = \lim_{z \to -j\infty} [w(z) - Im(z/g)] \tag{A-12}$$

where $w(z)$ is given by Eq. (A-10) related to the z-plane. In order to evaluate C'_{f0}/ϵ, it is necessary that both w and $Im(z/g)$ be expressed as functions of u. The limit must also be in terms of u. From Fig. A-1 it can be seen that as $z \to -j\infty$ along the path from C to A, then $u \to K + jK' - j\beta$ along the path from C to A. Thus

$$C'_{f0}/\epsilon = \lim_{u \to K + jK' - j\beta} \left[w(u) - Im \frac{z(u)}{g} \right] \quad . \tag{A-13}$$

Substitution of Eq. (A-2) into Eq. (A-10) gives

$$w(u) = \frac{1}{\pi} ln \left(\frac{1 + k \text{ sn } a \text{ sn } u}{1 - k \text{ sn } a \text{ sn } u} \right) \quad . \tag{A-14}$$

The limiting process is simplified by letting

$$u = K + jK' - j\beta - j\delta \tag{A-15}$$

where $\delta \to 0$ as $u \to K + jK' - j\beta$ along the path from C to A. Assuming very small δ, and using various elliptic function equivalences, such as may be found in Ref. 13, Eq. (A-14) reduces to

$$\underset{\delta \to 0}{w(u)} = \frac{1}{\pi} ln\ 2 - \frac{1}{\pi} ln \left(-j \frac{\text{cn } a \text{ dn } a}{\text{sn } a} \right) - \frac{1}{\pi} ln\ \delta \quad . \tag{A-16}$$

Cockroft's[12] Eq. (44) gives $z(\delta)$ as

$$z(\delta) = (K + jK' - j\beta)\left[1 - \frac{\mathrm{dn}\ a}{k^2\ \mathrm{sn}\ a\ \mathrm{cn}\ a} Z(a)\right] \tag{A-17}$$

$$- \frac{1}{2}\frac{\mathrm{dn}\ a}{k^2\ \mathrm{sn}\ a\ \mathrm{cn}\ a}\ ln\ \frac{\Theta(jK' - j\delta)}{\Theta(2a + jK' - 2j\beta)} \quad .$$

Using Eq. (A-17) with Eq. (A-6), and passing to the limit of δ approaching zero, gives

$$\lim_{\delta \to 0}\left[\frac{z(\delta)}{g}\right] = (K' - \beta)\left[\frac{1}{g} - \frac{2j}{\pi} Z(a)\right] + \frac{1}{\pi}\ ln\ \Theta(jK' - 2j\beta) \tag{A-18}$$

$$- \frac{K'}{4K} - \frac{1}{2\pi}\ ln\ \frac{2kk'K}{\pi} - \frac{1}{\pi}\ ln\ \delta \quad .$$

In Eqs. (A-17) and (A-18), the term Θ is Jacobi's Theta Function.[14] Now Eqs. (A-16) and (A-18) can be substituted into Eq. (A-13), yielding

$$C'_{f0}/\epsilon = \frac{1}{\pi}\ ln\ \frac{2j\ \mathrm{sn}\ a}{\mathrm{cn}\ a\ \mathrm{dn}\ a} + \frac{1}{2\pi}\ ln\ \frac{2kk'K}{\pi} + \frac{K'}{4K} \tag{A-19}$$

$$+ (K' - \beta)\left[\frac{2j}{\pi} Z(a) - \frac{1}{g}\right] - \frac{1}{\pi}\ ln\ \Theta(jK' - 2j\beta) \quad .$$

This is the final form in which odd-mode fringing capacitance will be presented.

3. EVEN-MODE CAPACITANCE

The two rectangular bars in Fig. II-1 are at the same potential when energized in the even mode, so that no electric field crosses the plane midway between them. Thus, a magnetic wall may be placed in this plane without disturbing the fields. This is indicated by the dashed line between E and F on the planes of Fig. A-1. The upper half of the plane is mapped into a strip of unit height on a t_1 plane in such a manner that the singularity at AG is removed to infinity by the transformation

$$t_1 = \frac{1}{\pi} \ln \left[\frac{t\ k\ \mathrm{sn}\ a + 1}{t\ k\ \mathrm{sn}\ a - 1} \right] \quad . \tag{A-20}$$

The t_1-plane is shown in Fig. A-3. Notice that the upper half of the t-plane maps into the strip directly below the $Re\ t_1$ axis. The positive half of this strip is next mapped onto the lower half of a t_2-plane, shown in Fig. A-3, by the transformation

$$t_2 = M - 1 + M \cosh \pi t_1 \tag{A-21}$$

where

$$M \stackrel{\Delta}{=} \frac{2}{1 + \cosh \pi t_1(F)} = -\frac{\mathrm{cn}^2\ a}{\mathrm{sn}^2\ a} \tag{A-22}$$

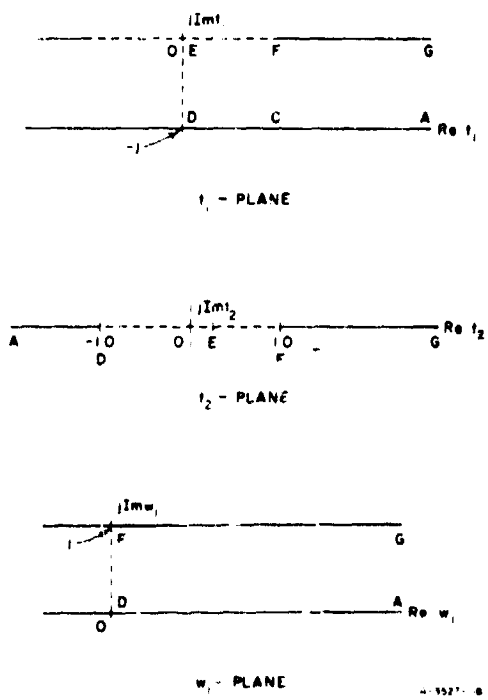

FIG. A-3 t-PLANE, t_2-PLANE, AND w_1-PLANE FOR EVEN-MODE CAPACITANCE

Finally, the desired parallel-plate configuration is achieved by mapping the lower half of the t_2-plane onto the positive half of a strip of unit height on the w_1-plane, using the transformation

$$w_1 = \frac{1}{\pi} \operatorname{arc\,cosh} (-t_2) \quad . \tag{A-23}$$

The w_1-plane is also shown on Fig. A-3. Combining Eqs. (A-2), (A-20), (A-21), (A-22), and (A-23) gives w_1 as a function of u:

$$w_1(u) = \frac{1}{\pi} \operatorname{arc\,cosh} \left\{ 1 + \frac{\text{cn}^2\, a}{\text{sn}^2\, a} + \frac{\text{cn}^2\, a}{\text{sn}^2\, a} \left[\frac{(k \text{ sn } a \text{ sn } u)^2 + 1}{(k \text{ sn } a \text{ sn } u)^2 - 1} \right] \right\} \quad . \tag{A-24}$$

As with the odd mode, it is convenient to use the variable δ, defined by Eq. (A-15), in passing to the limit. When Eq. (A-15) is substituted into Eq. (A-24) and appropriate approximations made for small δ, manipulation yields

$$\underset{\delta \to 0}{w_1(u)} = \frac{1}{\pi} \ln 2 + \frac{1}{\pi} \ln \left(-j \frac{\text{cn } a}{\text{sn } a \text{ dn } a} \right) - \frac{1}{\pi} \ln \delta \quad . \tag{A-25}$$

Using the definition of z-plane parallel-plate capacitance given in Eq. (A-11), the even-mode fringing capacitance, C'_{fe}/ϵ is

$$\frac{C'_{fe}}{\epsilon} = \lim_{\delta \to 0} \left[w_1(u) - Im \frac{z(u)}{g} \right] \quad . \tag{A-26}$$

Substitution of Eqs. (A-25) and (A-18) into Eq. (A-26) yields, after simplification,

$$\frac{C'_{fe}}{\epsilon} = \frac{1}{\pi} \ln \left(\frac{-2j \text{ cn } a}{\text{sn } a \text{ dn } a} \right) + \frac{1}{2\pi} \ln \frac{2kk'K}{\pi} + \frac{K'}{4K}$$

$$+ (K' - \beta) \left[\frac{2jZ(a)}{\pi} - \frac{1}{g} \right] - \frac{1}{\pi} \ln \Theta(jK' - 2j\beta) \quad . \tag{A-27}$$

This is the final form in which the even-mode fringing capacitance will be given.

4. DIFFERENCE OF FRINGING CAPACITANCES

The difference between fringing capacitances, $C'_{f0}/\epsilon - C'_{fe}/\epsilon$, is a very useful quantity because in most coupled structures it is also half of the difference between total odd-mode and even-mode capacitances. This difference is found by subtracting Eq. (A-27) from Eq. (A-19), yielding

$$\frac{C'_{f0}}{\epsilon} - \frac{C'_{fe}}{\epsilon} = \frac{1}{\pi} \ln \left(- \frac{\mathrm{sn}^2\, a}{\mathrm{cn}^2\, a} \right) . \qquad \text{(A-28)}$$

5. EVALUATION OF FORMULAS

The curves of C'_{fe}/ϵ and $C'_{f0}/\epsilon - C'_{fe}/\epsilon$ as functions of s/b and t/b were determined in the following manner. Values of $0 < k < 1$ were selected from tables[13,14] that determined K, K', and k'. Then for each value of k, a range of values of β/K' was selected from tables[15] that gave $\mathrm{sn}(\beta,k')$, $\mathrm{cn}(\beta,k')$, and $\mathrm{dn}(\beta,k')$. These functions are related to sn a, cn a, and dn a by

$$\begin{aligned} \mathrm{sn}(a,k) &= \frac{1}{\mathrm{dn}(\beta,k')} \\ \mathrm{cn}(a,k) &= jk' \frac{\mathrm{sn}(\beta,k')}{\mathrm{dn}(\beta,k')} , \\ \mathrm{dn}(a,k) &= k' \frac{\mathrm{cn}(\beta,k')}{\mathrm{dn}(\beta,k')} \end{aligned} \qquad \text{(A-29)}$$

The Zeta function can be expressed as

$$Z(a,k) = j \left[Z(\beta,k') + \frac{\pi\beta}{2KK'} - k'^2 \frac{\mathrm{sn}(\beta,k')\ \mathrm{cn}(\beta,k')}{\mathrm{dn}(\beta,k')} \right] , \qquad \text{(A-30)}$$

where

$$Z(\beta,k') = \frac{\Theta'(\beta,k')}{\Theta(\beta,k')} . \qquad \text{(A-31)}$$

The Theta functions were evaluated using a Fourier series expansion.[12] Values of t/b, s/b, C'_{fe}/ϵ and $C'_{f0}/\epsilon - C'_{fe}/\epsilon$ were then calculated from Eqs. (A-9), (A-27), and (A-28) and plotted as function of β/K', with k as parameter. Values of t/b were selected to be used as parameters on the final graph, and the related values of k and β/K' were taken from the t/b graph and tabulated. The values of k and β/K' at each point were used to determine related values of s/b, C'_{f_e}/ϵ, and $C'_{f0}/\epsilon - C'_{f_e}/\epsilon$ from their graphs. In this way it was possible to compile values of s/b, C'_{f_e}/ϵ and $C'_{f0}/\epsilon - C'_{f_e}/\epsilon$ for constant t/b. This compilation was used to plot the final sets of curves shown in Figs. II-3 and II-4.

REFERENCES

1. B. M. Oliver, "Directional Electromagnetic Couplers," *Proc. IRE*, 42,11, p. 1686 (November 1954).

2. E. M. T. Jones and J. T. Bolljahn, "Coupled-Strip-Transmission-Line Filters and Directional Couplers," *IRE Trans.* PGMTT-4, 2, p. 75 (April 1956).

3. S. B. Cohn, "Problems in Strip Transmission Lines," *IRE Trans.* PGMTT-3, 2, pp. 119-126 (March 1955).

4. G. L. Matthaei, "Design of Wide-Band (and Narrow-Band) Band-Pass Microwave Filters on the Insertion Loss Basis," *IRE Trans.* PGMTT-8, 6, pp. 580-593 (November 1960).

5. J. T. Bolljahn and G. L. Matthaei, "Microwave Filters and Coupling Structures," Report No. 1, Contract DA 36-039 SC-87398, Stanford Research Institute, Menlo Park California [illegible]

6. G. L. Matthaei, et al, "Design Criteria for Microwave Filters and Coupling Structures," Chapter 29, Final Report, SRI Project 2326, Contract DA 36-039 SC-74862, Stanford Research Institute, Menlo Park, California (January 1961).

7. G. L. Matthaei, "Design Theory of Up-Converters for Use as Electronically Tunable Filters," paper presented on May 5, 1961 at the 1961 PGMTT National Symposium in Washington, D.C. Also to be published in the September 1961 issue of the *IRE Trans. PGMTT*.

8. G. L. Matthaei, "Direct-Coupled, Band-Pass Filters with $\lambda_0/4$ Resonators," *1958 IRE National Convention Record*, Part 1, pp. 98-111 (1958).

9. D. C. Hogg and W. W. Mumford, "The Effective Noise Temperature of the Sky," *The Microwave Journal*, Vol. 3 pp. 80-84 (March 1960).

10. W. R. Smythe, *Static and Dynamic Electricity*, Chapter IV (McGraw-Hill Book Company, Inc., New York City, 1939).

11. Ernst Weber, *Electromagnetic Fields*: Theory and Applications, Vol. 1, "Mapping of Fields," (John Wiley and Sons, New York City, 1950).

12. J. D. Cockroft, "The Effect of Curved Boundaries on the Distributions of Electrical Stress Round Conductors," *Journal I.E.E. (Brit)*, Vol 66, pp. 385-409 (April 1926).

13. P. F. Byrd and M. D. Friedman, *Handbook of Elliptic Integrals for Physicists and Engineers* (Springer-Verlag, Berlin, 1954).

14. E. T. Copson, *Theory of Functions of a Complex Variable* pp. 405-407, (Oxford University Press, London 19).

15. G. W. Spenceley and R. M. Spenceley, *Smithsonian Elliptic Functions Tables*, (Smithsonian Misc Coll. Vol. 109, Washington, 1947).

DISTRIBUTION LIST

ORGANIZATION	NO. OF COPIES
Technical Library, OASD (R&E) Rm. 3E1065, the Pentagon, Washington 25, D.C.	1
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N. J., Attn: SIGRA/SL	1
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N. J., Attn: SIGRA/SL-AIT	1
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N. J. Attn: SIGRA/SL-ADJ (MF&A Unit No. 1 FUR Dept.)	1
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N. J., Attn: SIGRA/SL-TN (FOR RETRANSMITTAL TO ACCREDITED BRITISH AND CANADIAN GOVERNMENT REPRESENTATIVES)	3
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N. J. Attn: SIGRA/SL-LNF	3
Commanding Officer U.S. Army Signal Equipment Support Agency, Fort Monmouth, N. J. Attn: SIGMS/ADJ	1
Director U.S. Naval Research Laboratory Washington 25, D.C. Attn: Code 2027	1
Commanding Officer and Director U.S. Navy Electronics Laboratory, San Diego 52, California	1
U.S. Army Signal Liaison Office, ASD-9, Wright Aeronautical Systems Command, Building 50, Room 025, Wright Patterson Air Force Base, Ohio	2
Commander Air Force Command and Control Development Division, Air Research and Development Command, United States Air Force, L. G. Hanscom Field, Bedford, Massachusetts, Attn: CRUTLR-2	1
Commander Rome Air Development Center Air Research and Development Command, Attn: RCSSID, Griffiss Air Force Base, New York	1
Commander Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia	10
Advisory Group on Electronic Parts, Moore School Building, 200 S. 33rd Street Philadelphia 4, Pennsylvania	4
Commanding General Army Ordnance Missile Command Signal Office, Redstone Arsenal, Alabama	1
Chief, Bureau of Ships Dept. of the Navy Washington 25, D.C. Attn: 691B2C	1
Commander, New York Naval Shipyard, Materials Laboratory Brooklyn, New York Attn: CODE 910-d	1
Commanding Officer Diamond Ordnance Fuse Laboratories Washington 23, D.C. Attn: Technical Reference Section ORDTL-06.33	1
Commanding Officer, Engineering R&D Laboratories, Fort Belvoir, Virginia Attn: Technical Documents Center	1
Chief, U.S. Army Security Agency, Arlington Hall Station Arlington 12, Virginia	2
Deputy President U.S. Army Security Agency Board, Arlington Hall Station Arlington 12, Virginia	1
Microwave Engineering Laboratories, Inc. Palo Alto, California	[illegible]
Airborne Instruments Lab, Mineola, L.I., N.Y. Attn: Mr. R. Sleven	1
Commanding Officer U.S. Army Signal Research Unit Mountain View, California Attn: SIGRU-3	1

DISTRIBUTION LIST *Continued*

ORGANIZATION	NO. OF COPIES
Stanford Electronics Lab, Stanford University Stanford, California Attn: App. Elec. Laboratory	1
Convair, Pomona, Calfironia	1
Commander Rome Air Dev. Center Griffiss Air Force Base, N. Y. Attn: RCLTM-2, Mr. Patsy A. Romanelli	1
Commanding Officer U.S. Army Signal Research and Development Agency Fort Monmouth, N. J. Attn: SIGRA/SL-PRM (Mr. Reingold)	1
Rantec Corporation [illegible] Attn: S. B. Cohn, Tech Director	
Technical Library G. E. Microwave Laboratory 601 California Avenue Palo Alto, California	1
Dr. K. L. Kotzebue Watkins-Johnson Co., 3333 Hillview Avenue Stanford Industrial Park Palo Alto, California	1
Watkins-Johnson Company 3333 Hillview Avenue Palo Alto, California	1
Commanding Officer U.S. Army Signal Research and Development Agency, Fort Monmouth, N.J. [illegible]	22
Commanding Officer U.S. Army Signal Equipment Support Agency Fort Monmouth, N.J. Attn: SIGMS/SDM	1

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. L. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. L. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. K. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. K. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031 SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.

UNCLASSIFIED

A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.

UNCLASSIFIED

A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.

UNCLASSIFIED

A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.

UNCLASSIFIED

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. L. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. L. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. K. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

AD Accession No.
STANFORD RESEARCH INSTITUTE, Menlo Park, California

MICROWAVE FILTERS AND COUPLING STRUCTURES, by W. J. Getsinger and G. K. Matthaei.
Report No. 2, Second Quarterly Progress Report, 1 April to 30 June 1961, 39 pp. 16 Illustrations

Contract DA-36-039 SC-87398,
File No. 40553-PM-61-93-93
DA Project 3G26-12-031, SCL-2101K (20 April 1959)

Curves are presented giving the even-mode fringing capacitance, the odd-mode fringing capacitance, and the difference between them for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are given relating these capacitances to the even- and odd-mode characteristic impedances of coupled rectangular bars. Possible applications to strip-line and other circuits are described. The derivation of the capacitances by conformal mapping techniques is described in an appendix.

UNCLASSIFIED

1. Fringing capacitance of coupled rectangular bars between parallel plates
2. Electronically tunable up-converter
3. Coupled strip-lines
4. Microwave structures

A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.	UNCLASSIFIED	A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.	UNCLASSIFIED
A trial strip-line lower-sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.	UNCLASSIFIED	A trial strip-line lower sideband electronically tunable up-converter is described. This device uses a narrow-band, lower-sideband output circuit, and tuning at the input frequency is achieved by varying the pump frequency. Fast electronic tuning can be obtained by using a voltage-tunable pump oscillator. The measured 3-db bandwidth tuning range is 38.5 percent, compared to the 40-percent design objective, and the peak gain is 12.6 db. The input tuning band extends from 764 to 1128 Mc, and the sideband output is at 4,037 Mc. The midband noise figure is estimated to be 2.1 db.	UNCLAS

STANFORD
RESEARCH
INSTITUTE

MENLO PARK, CALIFORNIA

Regional Offices and Laboratories

SOUTHERN CALIFORNIA LABORATORIES
820 Mission Street
South Pasadena, California

WASHINGTON OFFICE
808 17th Street, N.W.
Washington 5, D.C.

NEW YORK OFFICE
270 Park Avenue, Room 1770
New York 17, New York

DETROIT OFFICE
The Stevens Building
1025 East Maple Road
Birmingham, Michigan

EUROPEAN OFFICE
Pelikanstrasse 37
Zurich 1, Switzerland

Representatives

HONOLULU, HAWAII
Finance Factors Building
195 South King Street
Honolulu, Hawaii

LONDON, ONTARIO, CANADA
85 Wychwood Park
London, Ontario, Canada

LONDON, ENGLAND
15 Abbotsbury Close
London W. 14, England

MILAN, ITALY
Via Macedonio Melloni 40
Milano, Italy